COMPARATIVE STUDY OF EFFECT OF DISPERSION ON DIFFERENT PULSE SHAPES IN AN OPTICAL FIBER LINK

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In Partial Fulfillment of the Requirements
For the Degree of
Master of Technology

by
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to the

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CERTIFICATE

This is to certify that the thesis work entitled " **COMPARATIVE STUDY OF EFFECT OF DISPERSION ON DIFFERENT PULSE SHAPES IN AN OPTICAL FIBER LINK"** submitted by Partha Sarathi Ghatak (Roll No- Y3104130) has been carried out under my supervision and the same has not been submitted else where for a degree.

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ABSTRACT

Performance of optical channels is mainly affected by either attenuation or dispersion. In this thesis, the later phenomenon is considered. Dispersion is the main criteria to limit the high data rate in an optical fiber link. Due to dispersion, pulse spreading takes place which increase the bit error rate. It is obvious from the communication theory that for different pulse shapes there will be different signal to noise ratio at the output. Hence, bit error rate will also be different. This thesis deals with the study and performance comparison of different pulse shapes in a dispersive optical link. Different pulse shapes are applied to a dispersive optical link and photo detector output is passed through a low pass filter. Three low pass filters are considered here – ideal LPF, first order LPF, second order LPF. Low pass filter output is sampled at sample and hold circuit and output sample is compared in a threshold detector. Additive white Gaussian noise is assumed to be present in the detector. Pulses are also studied in duobinary modulation. Duobinary modulation is a modulation scheme that is used to control dispersion. This scheme uses three level signals (-1,0,1) in terms of electric field and two level signals in terms of intensity. Dispersion is reduced for the existence of two opposite level signals (-1 and 1). Performance is measured in terms of bit error rate with duo binary modulation.

MATLAB is used for computing the results. We find that as slope increases from rectangular to triangular, power penalty also increases. It is also clear that for truncated Gaussian pulse, performance is worse for lower sigma and it tends to be same as the rectangular one as sigma increases. For some pulses, power penalty is negative when first order LPF is used. This implies that the system is performing well with dispersion than without dispersion with first order filter. This happens due to better compatibility of first

order filter with dispersive channel. From bit error rate and power penalty plot we find better performance using duobinary modulation and second order low pass filter.

So, it can be concluded that using rectangular pulse shape, duobinary modulation and, second order LPF at the receiver better performance can be obtained.

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Finally, I would like to thank my parents for giving constant inspirations throughout my career.

Partha Sarathi Ghatak

To

The Almighty

Abbreviations:

BER	bit error rate
CSF	conventional single mode fiber
DCF	dispersion compensating fiber
e-h	electron- hole
GHz	gigahertz
LED	light emitting diode
MHz	megahertz
μm	micrometer
μs	microsecond
nm	nanometer
NRZ	non return to zero
ns	nanosecond
PIN	p(doped) intrinsic n(doped)
ps	picosecond
RZ	return to zero
SNR	signal to noise ratio
WDM	wavelength division multiplexing

TABLE OF CONTENTS

CHAPTER 3: MODEL OF OPTICAL COMMUNICATION LINK

CHAPTER 5: DUO BINARY MODULATION

CHAPTER 5: COMPARATIVE STUDY OF DIFFERENT PULSE SHAPES

CHAPTRE 6: CONCLUSION AND SUGGESION FOR FUTURE WORK

CHAPTER 1

Introduction

1.1 Need for Optical Communication

In the advent of 21^{st} century we see a burgeoning demand on communication network assets for services such as database querries and updates, home shopping, video-on-demand, remote education, tele-medecine, video conferencing. This demand was fueled by the rapid proliferation of personal computers(PCs) , coupled with a phenomenal increase in their storage capacity and processing capabilities, the wide spread availability of the internet and on extensive choice of remotely accessible programs and information databases. To handle the ever increasing demand for high BW services from user ranging from home based PCs to business and research organizations, telecommunication companies worldwide are using light waves, traveling within optical fibers as the dominant transmission system. Optical fiber is the only transmission medium offering such large bandwidth. Optical fiber also provides the low loss communication links as compared to radio or electrical cables. In addition to large bandwidth and low loss, there are many other advantages of using optical fiber. Optical fibers are immune to electromagnetic interference. Optical links are more reliable and can support future application due to inherently large available capacity. Optical fiber links are best suited for fixed user locations. This optical transmission medium consists of hair thin glass that guides the light signal over long distance.

To send the services (e.g. Voice, video, data services) from one user to another, network providers combine the signals from many different users and send the aggregate signal over a single transmission line. This is known as multiplexing. In, commonly used time division multiplexing, N independent information streams each running at a data rate of R bits/second, are interleaved electrically into a single information stream

operating at a higher rate of N×R bits/second. To get a detailed perspective of this let us look at the multiplexing schemes used in telecommunication.

Early applications of fiber optic communication links were largely for trunking of telephone lines. These were digital links consisting of time division multiplexed 64 kbps voice channels. Fig1 shows the digital transmission hierarchy used in the North American telephone network. The functional building block is a 1.544 Mbps transmission rate known as T1 rate. It is found by the time division multiplexing of 24 voice channels to yield the 1.544Mbps bit stream. At any levels a signal at the designated input rate is multiplexed with other input signals at the same rate.

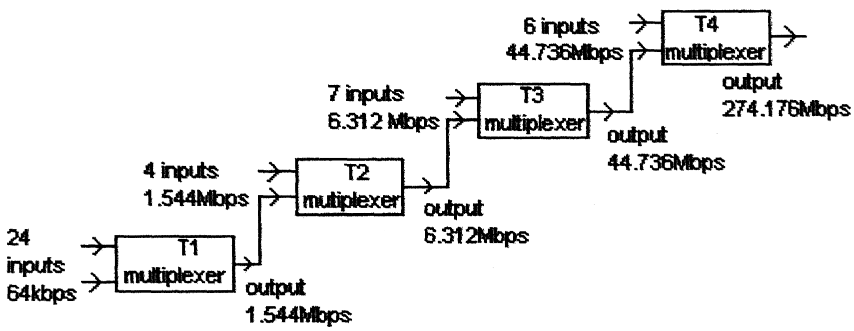


Fig 1.1 Digital transmission hierarchy

The system is not restricted to multiplexing of voice signals. For example, at the T1 level , any 64Kbps digital signal of the appropriate format could be transmitted as one of the 24 input channels shown in fig 1. As noted in fig 1, the rate of multiplexing designated as T1(1.544Mbps),T2(6.312Tbps),T3(44.736Mbps) and T4(274.176Mbps). With the advent of high capacity fiber optic transmission lines in the 1980's, service providers established a standard signal format called synchronous optical Network(SONET), in North America and synchronous digital hierarchy(SDH) in other parts of the world standards define a synchronous frame structure for sending multiplexed digital traffic over optical fiber trunk lines.

1.2 The Evolution of Fiber Optic System

Since the interception of optical fiber communication in 1974, their transmission capacity has experienced a 10 fold increase every 4 years. Several major technology advances spurred this growth. Fig-2 shows the operating range of optical fiber systems and the characteristics of the four key component of a link.The optical fiber light

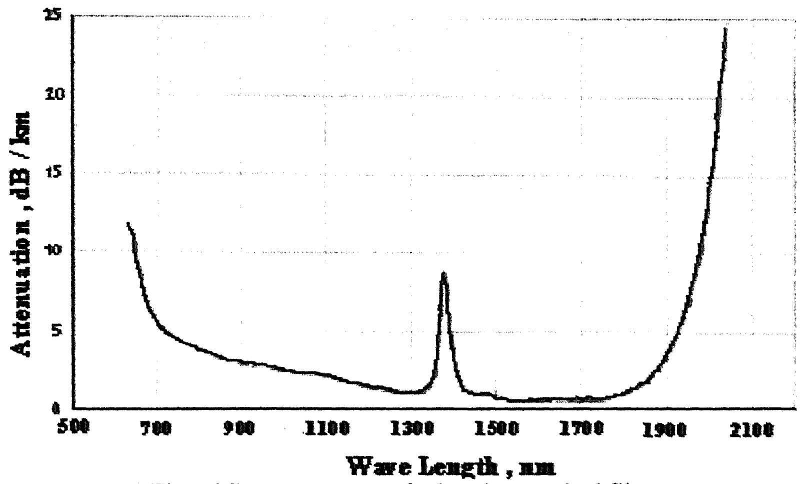


Fig 1.2 Loss spectrum of a low loss optical fiber

sources, photo detectors and optical amplifiers. The first generation links operated at around 850nm, which was a low loss transmission window of early silica fibers. These links used existing GaAs based optical sources silicon photo detector sand multimode fibers. Inter modal dispersion and fiber loss limited the capacity of the systems. Some of the intermodal telephone system field trials in the USA were carried out in 1977 by GTE in Los Angles and by AT & T in Chicago. Links similar to this were demonstrated in Europe and Japan.

The development of optical sources and photo detectors capable of operating at 1300 nm allowed a shift in the transmission wavelength from 800nm to1300 nm. The result is a substantial increase in repeater less transmission distance for long haul telephone trunks, since optical fibers exhibit lower power loss and, less signal dispersion at 1300 nm.

Dispersion is the major problem in optical fiber which supports high bit rate. Due to dispersion different frequency component of the pulse reaches at different time which

give rise to pulse spreading as shown in the figure. Due to pulse spreading ISI occurs which increases significant amount of bit error rate.

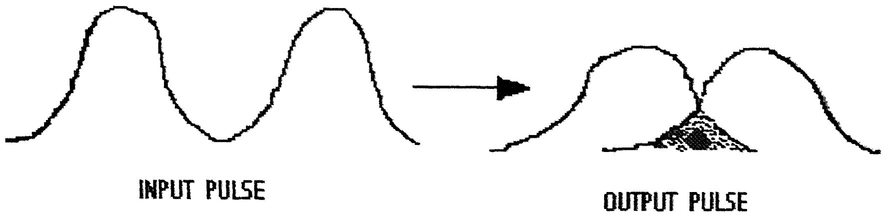


Fig 1.3 Dispersion of pulse

System operating at 1550 nm provide the lowest attenuation, but standard silica fiber have a much larger dispersion at 1550nm than at 1300 nm. Fiber manufacturers overcome this limitation by creating the so called dispersion shifted fiber. Thus, 1550 nm systems attracted much attention for high capacity long span terrestrial and, under sea terrestrial links. These links routinely carry traffic at around 2.5 Gbps over 90 km repeater less distances. By 1996, advances in high quality lasers and receivers allowed single wavelength transmission rates around 10Gbps.

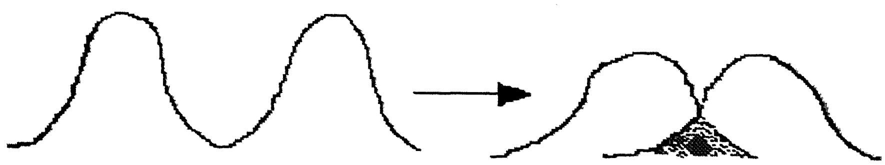
1.3 Basic Characteristics of the Optical Fiber

An optical waveguide is a structure that can guide a light beam from one place to another. The most extensively used optical waveguide is the step index optical fiber, that consists of a cylindrical central dielectric core, clad by a dielectric material of a slightly lower refractive index. The corresponding refractive index at distance r from centre of cylindrical fiber is given by,

$$\begin{aligned} n(r) &= n_1 \qquad 0 < r < a \quad \text{in core} \\ &= n_2 \qquad r > a \quad \text{in cladding} \end{aligned}$$

Here, r represent the cylindrical radial co-ordinate and a represents the radius of the core. Actually, the core extends only to a finite distance b. However, for all theoretical formulations we will assume the cladding to extend to infinity as this does not introduce much error in results and models are valid for actual fibers also. If, the angle of incidence

give rise to pulse spreading as shown in the figure. Due to pulse spreading ISI occurs which increases significant amount of bit error rate.



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(at the core cladding interface) ϕ is greater than the critical angle, $\phi_c = sin^{-1} (n_2 / n_1)$ then, the ray will get guided through the core by repeated total internal reflection.

If a large number of fibers are put together, this forms what is known as a bundle. If fibers are not aligned properly, that is if the position of the fibers in the input and output ends are the same, the bundle is said to form a coherent bundle.

1.4 Elements of an Optical fiber link

An optical fiber transmission link comprises the various elements. Transmitter consisting of a light source and, it's associated drive circuitry, cable offering mechanical and environmental protection to the optical fiber contained inside, receiver consisting of a photo detector pulse amplification and signal restoring circuitry. Additional components along the link include optical amplifiers, connectors, splices, couplers and regenerators (for restoring the signal shape characteristics). The cabled fiber is one of the most important elements in an optical fiber link. In addition, to protect the glass fibers at the time of installations and service, the cable contain copper wires. These are also used for powering optical amplifiers, or signal regenerators which are needed periodically for amplifying and reshaping the signals in long distance links.

One of the principal characteristics of an optical fiber is it's attenuation as a function of wavelength as shown in fig 1.2. Early technology made exclusive use of the 800-900 nm wavelength, since in this region the fiber made at this time exhibited a local minimum in the attenuation curve. Optical sources and photo detectors operating at this wavelength were readily available. By reducing concentration of hydroxyl ions and metallic impurities in the material manufactures were able to fabricate optical filters with very low loss in the 1100-1600 nm region.

Once the cable is installed, a light source that is dimensionally compatible with the fiber core is used to launch optical power into the fiber. Semiconductor light emitting diodes (LEDs) and laser diodes are suitable for this purpose. In the 800 to 900 nm region, the light sources are generally alloys of GaAlAs. At larger wavelengths, (1100-1600 nm), an InGaAsP alloy is the principal optical source material.

1.5 Thesis Objective

It is obvious from communication theory that the shape of the input pulse gets affected in a dispersive channel. In optical fiber systems also, the input pulse shape gets affected by various types of dispersion phenomena - material dispersion, waveguide dispersion, modal dispersion, and polarization dispersion.

The present work focuses on studying the impact of material dispersion of fiber optic channel on various pulse shapes of the signal with different receiver filter.

Also, the impact of dispersion on the pulse shape for a duobinary modulated signal in an optical fiber is investigated.

CHAPTER 2

Pulse Dispersion

2.1 Pulse Dispersion in Optical Fiber

Pulse dispersion represents one of the most important characteristics of optical fiber that limits the information carrying capacity of the communication system.

In digital communication system, information to be sent is first coded in the form of pulse, and the pulses of light are transmitted from the transmitter to the receiver where the information is decoded.The larger the no of pulses that can be sent per unit time while still be reasonably decoded at the receiver end, the larger will be transmission capacity of the system. A pulse of light which is sent into fiber broadens in the time as propagates through the fiber. This phenomenon is known as pulse dispersion and happens primarily for two reasons.

(1) Different rays take different time to propagate through a given length of the fiber.

(2) Any given source emits over a range of wavelengths, and because of the intrinsic property of the material, different wavelength take different amount of time to propagate along the same path.(also referred to as material dispersion)

2.2 Different Types of Dispersion

a) Material dispersion : Material Dispersion is a delay time dispersion caused by the fact that the refractive index of the glass material changes in accordance with the change of the signal frequency (or wave length). This nonlinearity of the refractive index causes a nonzero value for $(d^2\beta/d\omega^2)$ which gives rise to dispersion. Here β is propagation constant and ω is angular frequency of wave propagating in waveguide.

b) Waveguide dispersion: Waveguide dispersion is a delay time dispersion caused by the confinement of light in the waveguide structure. The dependence of the propagation constant β (or normalized propagation constant b) on the angular frequency ω (or normalized frequency v) is nonlinear for light propagation in the waveguide. Therefore waveguide dispersion is an essential dispersion that inevitably exits in wave guide.

c) Multi mode dispersion: Multimode dispersion is the delay time dispersion caused by the difference of group velocity of the various modes. There will be different group velocities for different modes. Therefore multimode dispersion will be present. This dispersion does not present in single mode fibers.

d) Polarization mode dispersion: Polarization mode dispersion is delay time difference between the orthogonal polarized modes in the birefringent fibers. The slight birefringence in the single mode fiber is caused by the nonconcentricity of the core and the ellipticity of the core. This ellipticity and nonconcentricity is not present in single mode fibers which we are considering. Hence, we can neglect this effect.

2.3 Computation of Material Dispersion

Any source of light have a spectral width $\Delta\lambda_o$ and each of the spectral component would in general travel with a different group velocity, we would always have dispersion. This is material dispersion. If the pulse propagates in a homogenous medium with a group velocity $v_g = 1/(dk/d\omega)$; where, $k(\omega) = (\omega/c).\ n(\omega)$; where $n(\omega)$ represents the frequency dependent refractive index .

Thus, $(1/v_g) = dk/d\omega$

$$= \left(\frac{d}{d\omega}\right)\left(\frac{\omega}{c}\right).n(\omega)$$

or, $(1/v_g) = (1/c).[\,n(\omega) + \omega.\,(dn/d\omega)\,];$

usually, one expresses the group velocity in terms of the free space wavelength λ_o ,which is related to the frequency through the following relation ,

$$\omega = (2.\pi.c / \lambda_0)$$

Thus, $\omega.(dn/d\omega) = (2.\pi.c/\lambda_0).[(dn/d\lambda_o)(-2.\ \pi.c/\omega^2)];$

$= -\ \lambda_o\ .\ (dn/d\lambda_o)\ ;$

So, $(1/v_g) = (1/c).[n(\lambda_o) - \lambda_o.(dn/d\lambda_o)];$

Thus the time taken by a pulse to traverse length L of fiber is given by ,

$$\tau = \tau(\lambda_o) = (L/v_g) = (L/c).[\,n(\lambda_o) - \lambda_o.(dn/d\lambda_o)];$$

which is dependent on the wavelength λ_o . The quantity, $N(\lambda_o) = n(\lambda_o) - \lambda_o.\ (dn/d\lambda_o);$ is also referred to as the group refractive index ,since $c/N(\lambda_o)$ gives the group velocity. If the source is characterized by spectral width $\Delta\lambda_o$, then each wavelength component will traverse with a different group velocity , resulting in temporal broadening of the pulse.

2.4 Transfer Function of Dispersion

Here, we want to determine the transfer function of a fiber, when dispersion is present. A plane monochromatic wave propagating along the z axis through homogenous medium is described by , $\psi = A.e^{\,i.(\omega.t\ -\ k.z)}$; Here, we consider a temporal pulse described by ,the function ,

$$\psi(z=0,t) = \int_{-\infty}^{+\infty} A\,(f).e^{i.2.\pi.f.t}\,df$$

where , $A(f) = |A(f)|.\ e^{i.\ \phi(f)}$;

$$\psi(z,t) = e^{-i.k.z} \int_{-\infty}^{+\infty} A\,(f).e^{i.2.\pi.f.t}\,df = \int_{-\infty}^{+\infty} A\,(f).e^{i\,(2.\pi.f.t-k.z)}\,df$$

$$\psi(z,t) = \int_{-\infty}^{+\infty} A\,(f).e^{i\,(2.\pi.f.t-k.z)}\,df$$

$$\Psi(z,f) = |A(f)|.e^{i.\ \phi(f)}.\ e^{-\,i.k.z}\ ;$$

So, Transfer Function $= (\Psi(z,f) / \Psi(0,f)) = e^{-i\,.\,k.z}$;

where, $k(\omega) = k(\omega_0) + (dk/d\omega)|_{\omega=\omega_0} . (\omega - \omega_0) + (1/2).(d^2k/d\omega^2)|_{\omega=\omega_0} (\omega-\omega_0)^2 + \ldots\ldots$

Now, if we take $\omega_0 = 0$, that is we want to expand around $\omega = 0$, then,

$k(\omega) = k(0) + (dk/d\omega)|_{\omega=0} . \omega + (1/2).(d^2k/d\omega^2)|_{\omega=0} . \omega^2 + \ldots\ldots\ldots$

Now, if we consider $(dk/d\omega)|_{\omega=0} = \beta_1$ and, $(d^2k/d\omega^2)|_{\omega=0} = \beta_2$

Then Transfer function $= e^{-i(k(0)+\beta_1\omega+\left(\frac{1}{2}\right)\beta_2\omega^2)L}$;

$= e^{-i(k(0)+\beta_1.2\pi.f+\left(\frac{1}{2}\right)\beta_2.(2.\pi.f)^2)L}$;

Now, for k(0) and, $\beta_1 .2.\pi.f$, there will be no change of output signal at the time domain. So, only $(1/2).\beta_2 .(2.\pi.f)^2$ is responsible for dispersion.

So, the Transfer Function is $= e^{-i.(1/2).\beta_2 (2.\pi.f)^2 L}$;

$= e^{i.v(\pi fT)^2}$;

Where, v is defined as normalized dispersion index $v = -2.\beta_2 . L . R^2$

β_2 is the chromatic dispersion parameter and L is the fiber length and R is the bit rate (R = 1/T).

$d^2k / d\omega^2 = (1/c).(\lambda_0^2 / 2.\pi.c).\lambda_0.(d^2n / d\lambda^2_0)$

$= (-\lambda_0^2 / 2.\pi.c).(-1/c\lambda_0).(\lambda_0^2. d^2n / d\lambda^2_0)$

$= (-\lambda_0^2 / 2.\pi.c).D$,

Where, $D = -\frac{\lambda_0^2 (d^2n/d\lambda_0^2)}{c.\lambda_0}$ (D is the dispersion factor, unit ps /km-nm)

Hence, $v = -2.\beta_2 . L . R^2$

$= (-2).(-\lambda_0^2 / 2.\pi.c) D . L. (1/T)^2$

$= (\lambda_0^2 /\pi.c). D. (L / T^2)$;

2.5 Different Methods to Control Dispersion

2.5.1 Using Waveguide Dispersion to Compensate Material Dispersion

It is found that the waveguide dispersion is negative in the single mode region. Since the material dispersion is positive for λ_0 greater than the zero material dispersion wavelength, there is a wavelength at which the negative waveguide dispersion will compensate the positive material dispersion . At this wavelength the net dispersion of the single mode fiber is zero and, this wavelength is referred to as the zero dispersion wavelength . Single mode fiber with zero dispersion around 1300nm are referred to as the conventional single mode fibers#(CSF).

2.5.2 Using Dispersion Compensating Fiber

Operation around $\lambda_0 \simeq$ 1300 nm leads to very low pulse broadening, but the attenuation is higher than at 1550 nm. Thus, to exploit the low loss window around 1550 nm new fiber designs were developed that had zero dispersion in the 1550 nm wavelength region .These fibers are referred to as dispersion shifted fiber#(DSF).

In many countries, tens of millions of kilometers of CSFs already exist in the underground ducts operating at $\lambda_0 \simeq$ 1300 nm. One could increase the transmission capacity by operating these fibers at 1550 nm and , using WDM techniques and optical amplifiers. But, then there will be significant residual dispersion. On the other hand , replacing the fibers by DCFS would involve huge costs. So, there has been considerable work in upgrading the installed 1310 nm optimized optical filter links for operation at 1550 nm. This is achieved by developing fibers with very large negative dispersion coefficients; a few hundred meters to a kilometer, which can be used to compensate for dispersion over tens of kilometers of the fiber in the link. This is known as dispersion

compensating fibers#(DCF). Since the DCF has to be added to an existing fiber optic link, it would increase the loss of the system and hence would pose problems in detection at the end.

2.5.3 Dispersion Compensation Using Bragg Grating

An input pulse dispersed after propagating along a telecommunication fiber is directed to the grating, where the shorter wavelengths penetrate deeper into the grating before they will be reflected. This effect is achieved by shortening the grating period at the grating entrance and lengthening it at the grating end. Thus the device consumes less of delay for longer wavelengths. This is exactly the opposite of the delay introduced by a single mode fiber itself. Therefore, pulse spread caused by chromatic dispersion in telecommunication fiber is compensated by a chirped Bragg grating.

2.5.4 Dispersion Control Using Pulse Shape

Due to dispersion in optical fiber pulse gets broadened, causing inter symbolic interference which leads to bit error rate. If proper pulse shape is chosen, it is possible to minimize bit error rate caused by dispersion because, from communication theory we know that when impulse response of matched filter is, $g(t) = p^*(-t)$ where, $p(t)$ is the transmitted pulse, signal to noise ratio becomes maximum. This method to control dispersion can be used along with other methods. By using duobinary modulation, where we use three levels of pulses, if proper pulse shape is chosen, dispersion effect can be further reduced.

CHAPTER 3

Model of Optical Communication Link

3.1 Optical Source Semiconductor LASER

In it's simple form, a semiconductor laser consists of a forward biased p-n junction, formed in a direct band gap semiconductor. The recombination of injected carriers namely electrons and holes – in the junction region results in the emissions of photons. Waveguide structure is formed by suitable doping in the junction region. This also confines carriers due to reduced bandgap. The ends of this waveguide structure is cleaved to form the reflecting surfaces required for the lasing. Typical dimensions of a discrete laser diode chip are shown in the figure. When the forward current through the diode exceeds a critical value known as the threshold current , optical gain in the resonator due to stimulated emissions overcomes the loss in the resonator, leading to net amplification and, eventually to steady state laser oscillations.

Silica based optical fibers have low loss windows around 1300nm and, 1500nm wavelengths. Therefore to operate at these wavelength, one has to choose a corresponding direct bandgap energy. Accordingly the natural system that is widely used in fabrication of the laser diode for optical communication in the 1300nm and, 1500nm window is InGaAsP / InP (InP indium phosphide).

3.2 Mach – Zehnder Modulator

One of the most sensitive arrangements of a fiber optic sensor is Mach-Zehnder interferometric sensor shown in fig3.1. Light from a laser is passed through a 3 dB fiber optic coupler, which splits the beam equally into the two single mode fiber arms. After traversing the fiber length , the two fibers form inputs to another 3dB coupler, which helps in superposing the two beams. In a bulk Mach-Zehnder interferometer , the two 3dB couplers are beam splitters. The two outputs of the output coupler arms are first

detected and then processed. One of the arms of interferometer is the sensing arm which is used to change the phase of beam as per modulating signal. The other arm, called the reference arm acts as reference for phase perturbation. When an external parameter acts on the sensor, it alter the phase of the light propagating through sensingarm by changing the refractive index and/or the length of the sensing arm. At the same time since, the light propagating in the reference arm is unaffected, i.e. external perturbation has no influence on the phase. Thus as the two beams enter the second 3dB coupler, the powers exciting from the two output arms will be determined by the phase difference between the two beams.

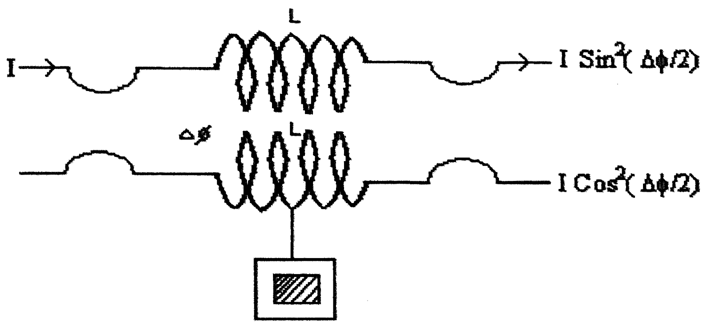

Fig 3.1 Mach – Zehnder Modulator

A measurement of the output intensities gives us the parameter to be measured. Indeed, if ϕ_1 and, ϕ_2 are the phases of the two beams as they enter the output 3 dB coupler then one can show that ,

$$I_1 = I_0 \, Cos^2 (\Delta\phi/2) ;$$

$$I_2 = I_0 \, Sin^2 (\Delta\phi/2) ;$$

where, I_0 is the input intensity , I_1 and I_2 are the output intensities from arms 1 and 2 and, $\Delta\phi = \phi_1 - \phi_2$; Thus if the signal and, reference arms introduce identical phase shifts then, $\Delta\phi = 0$ and, all power exits from output1. Similarly, for a phase difference of π, all power exits from output2. For all other values, power gets divided into two so that , $I_1+I_2 = I_0$;

So, here in one of the arms, we are introducing phase shift by using electrooptic effect where, change of the refractive index is proportional to the applied electric voltage signal. The shape of electrical pulse decides the optical pulse shape. So, at the output we are getting optical signal as the shape of input pulse.

3.3 Channel

Fiber optic channel is used here. An optical fiber is a di-electric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form. It confines electromagnetic energy in the form of light within it's surfaces and guides the light in a direction parallel to it's axis. The transmission properties of an optical waveguide are dictated by it's structural characteristics which have a major effect in determining how an optical signal is affected as it propagates along the fiber. The structure establishes the information carrying capacity of the waveguide by shielding the environmental perturbations. The fiber produces pulse dispersion. The dispersion effect at high data rate is described in chapter#2.

3.4 Optical Detector and Receiver

Receiver consists of detector, filter, sample and hold circuit and threshold detector.

I) Detectors for Optical Fiber Communication

An optical detector is a device that converts light signals into electrical signals, which can then be amplified and processed. Such detectors are one of the most important components of an optical fiber communication system and dictate the performance of a fiber optic communication link. There are many different types of photo detectors such as photomultiplier tubes, vacuum photo diodes and semiconductor photo diodes. Semiconductor photo diodes are most commonly used detectors in optical fibers(being small in size) and are of relatively low cost. These photo diodes are made from semiconductors such as silicon or germanium or from compound semiconductors such as GaAs , InGaAs etc.

There are two types of photo diodes most commonly used -PIN (doped, intrinsic, and n doped layers) diode and avalanche photo diodes (APD) . Important characteristics that are of particular relevance to optical fiber communication systems are discussed now on.

a) Principle of Optical Detection :

The principle behind photo detection using semiconductors is optical absorption. When light is incident on a semiconductor, light may or may not get absorbed depending on it's wavelength. If the energy hν of a photon of the incident light beam is greater than the band gap of the semiconductor, then it can be absorbed, leading to generation of e-h (electron – hole) pairs which are swept away, under the influence of electric field under reverse bias leading to a photo current in the external circuit.

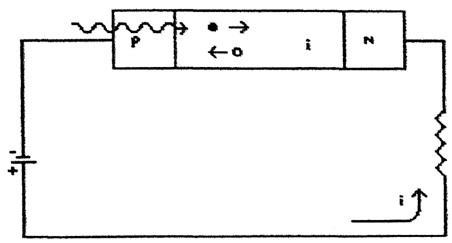

Fig 3.2 A reverse biased PIN photodiode

If E_g is the band gap of the semiconductor then maximum wavelength absorption is given by,

$$\lambda_c=(h.c/E_g)$$

The band gap energies are 1.11ev for silicon , 0.67 ev for germanium, 1.43 ev for GaAs, and 0.75 ev for InGaAs.Thus the corresponding cut off wave-lengths are 1.13μm, 1.85 μm, 0.87μm , 1.65 μm respectively implying that , the semiconductors can be used for detection of light below the cut off wave length.

b) PIN Photo Detector :

The most common semiconductor photo detector is the PIN photo diode which consists of an intrinsic (very lightly doped) semiconductor sandwiched between a p-doped and, an n- doped region. The PIN photodiode is normally subjected to a reverse bias. Since the intrinsic region has no free charges, it's resistance is high and hence most of the voltage across the diode appears across the **i** region. The **i** region is usually wide so that, incoming photons have a greater probability of absorption in the **i** region . Any e-h pairs generated in the p and n region have to first diffuse into the depletion region before being swept away. Also, there e-h pairs may suffer recombination, resulting in a reduced current.

c) Responsivity and Quantum Efficiency :

The absorption of optical radiation in the semiconductor material is described by ,

$$P(z) = P_0 [1- e^{-\alpha(\lambda).z}];$$

Where , P(z) is the optical power absorbed over distance z and α (λ) is the wavelength dependent absorption coefficient . Near cut off α rises more rapidly for GaAs , InGaAs and InGaAsP than for silicon and germanium. This is because Si and Ge have an indirect bandgap whereas the others have a direct bandgap and absorption coefficients are in the range of $10^3 - 10^5$.

Let, w represent the width of the depletion region. An optical power P_0 incident on the photo detector first suffers a partial reflection at the air semiconductor surface before entering the detector. If R represents the reflection coefficients , then the optical power entering the detector is P_0 *(1-R)*. The optical power absorbed in a distance w will then be, $P_0 (1-R)[1- e^{-\alpha(\lambda)w}]$;

If ν is the frequency of the incident light, then the number of photons absorbed per unit time $(P_0/h\nu)(1-R)(1- e^{-\alpha w})$

Since , each absorbed photon leads to generation of an e-h pair the above expression also gives the number of e-h pairs generated per time, assuming that analytical function ε of the e-h pair constitute photo current (the remaining have been lost due to recombination) Thus , the photo current is ,

$$I = (e/h\nu).(1-R)\varepsilon(1- e^{-\alpha w}) P_0$$

where , e is the magnitude of the electronic charge

The quantum efficiency η is the ratio of the number of e-h pairs generated to the number of incident photons. Thus,

$$\eta = (I/e)/(P_0/h\nu) = (1-R)\xi(1- e^{-\alpha w})$$

the responsivity ρ is the photo current generated per unit optical power and is usually specified in A/W.

$$\rho = I / P_0 = (\eta e / h\,\nu)\ (1-R)(1- e^{-\alpha w});$$

substituting for e(= 1.6×10^{-19} C) and , h (= 6.63×10^{-34} J.S)

equation can be rewritten as , $\rho = (\lambda_0 / 1.24)\,\eta$, with λ_0 measured in micrometers.

As an example, InGaAs has wavelength range 900-1700nm Responsivity--0.63-0.8, quantum efficiency 60-70% gain 1, dark current 1-20 mA

II) Filter

Photo detector output is passed through a low pass filter. Three types of low pass low pass filters have been considered by us. Here, f_c is defined as cut-off frequency of the LPF.

a) Ideal low Pass Filter :

$$\text{Transfer Function, } H(f) = \begin{cases} 1 & \textit{For } -fc < f < fc \\ 0 & \textit{Otherwise} \end{cases}$$

b) First Order Low Pass Filter :

$$\text{Transfer Function, } H(f) = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}}$$

c) Second Order Low Pass filter :

$$\text{Transfer Function, } \quad H(f) = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^4}}$$

III) Threshold Detector :

Threshold detector is circuit which computes the output sample with a threshold and, it determines whether it is logical one or logical zero.

3.5 Noise in Detection Process

When light falls on a photo detector, e-h pairs are generated which give rise to an electrical current. This conversion process from light to electrical current is accompanied by the addition of noise.

a) Shot Noise Shot noise arises from the fact that an electric current is made up of a stream of discrete charges namely electrons which are randomly generated. Thus even when a photo detector is illuminated by constant optical power P, due to random generation of e-h pairs , the current will fluctuate randomly around an average value determined by the average optical power P. Shot noise current has it's average value zero. We can define a mean squire shot noise current that can be shown to be

$\overline{I_{NS}^{\ 2}} = 2.e.I.\Delta f$ where, e is the electron charge, I is the average current generated by the detector and Δf is the bandwidth over which the noise is being considered. Since the photo current I itself depends on the incident optical power, the shot noise increases with an increase in incident power.

We need to mention here, that even in the absence of any optical power, all photo detectors generate some current I_d which arises from thermally generated carriers. This is dark current and increases with increase in temperature. So, shot noise current becomes $\overline{I_{NS}}^{2} = 2.e.(I + I_d).\Delta f$

b) Thermal Noise Thermal noise arises in the load resister of the photo diode circuit due to random thermal motion of electrons. In fact, electrons in any resister are never stationary but have random motions within the resistor. Since, motion of electrons constitute a current, this random thermal motion leads to the presence of a random current in the resister. This thermal noise adds to the signal current generated by the photo detector. The mean square thermal noise current in a load resister R_L is given by

$\overline{I_{NT}}^{2} = \left(\frac{4.k_B.T.\Delta f}{R_L} \right)$ where, $k_B = 1.38\times 10^{-23}$ J/K is the Boltzman constant , T is the absolute temperature.

3.6 Signal to Noise Ratio :

Signal to noise ratio is an important parameter in detection. It is defined by ,

$$\text{SNR} = \frac{\text{Average Signal Power}}{\text{Total Noise Power}}$$

If P represents the optical power incident on a photo detector with a responsivity R, then the signal current is R.P and, the electrical signal power is proportional to R^2P^2.

The total noise power is proportional to the total mean squire noise current, which is the sum of shot noise and, thermal noise terms. Thus,

$$SNR = \frac{R^2 P^2}{2.e.(I + I_d).\Delta f + \frac{4.k_B.T}{R_L}.\Delta f}$$

In the above equation, defining SNR, usually one of the noise terms in the denominator (shot noise or thermal noise) dominates depending upon the operating conditions.

The minimum detectable optical power corresponds to the situation when the signal power and, noise power are equal. This optical signal power is referred to as noise equivalent power or NEP and usually quoted in units of W/√ Hz . Assuming that the minimum power will be so low that $I_d >> I$, we obtain an expression for NER by putting SNR = 1;

$$NEP = \frac{1}{\sqrt{2.e.I_d + \frac{4.k_B.T}{R_L}}}$$

3.7 Bit Error Rate

Bit error rate is also an important parameter. If there is insufficient power in the received optical pulses, if there has been a large dispersion, or if too much noise is added by the detector then there could be errors in retrieved information . Bit error rate (BER) is defined by,

$$\text{BER} = \frac{\text{Average no of bits received erroneously in a duration } \tau}{\text{Total no of bits received in } \tau}$$

It is related to Signal to Noise Ratio.

We have assumed White Gaussian Noise at the input of the detector. While it passes through the LPF it becomes coloured noise but it's probability density function still remains Gaussian at the output.

i) Of ideal LPF, Noise variance $= 2.f_c.N_0$

ii) Of first order LPF, Noise variance $= \pi.N_0.f_c$

iii) Of second order LPF, Noise variance $= \pi.N_0.f_c / \sqrt{2}$

Here, N_0 = Power spectral density of white Gaussian Noise

f_c = Cut-off frequency of the LPF's as mentioned earlier

We are assuming that I and I_d is small so that, the system is thermal noise limited, and, $N_0 = 2.k_B.T.R_L$ (unit volt^2/Hz)

CHAPTER 4

Duobinary Modulation

4.1 Introduction:

Optical systems by and large use NRZ modulation, while NRZ is suitable for long haul systems in which the dispersion is always present. Duobinary modulation turns out to be a much better choice in the case since it is more resilient to dispersion and is also reasonably as simple to implement as NRZ.

Duobinary modulation is a scheme for transmitting R bit / Sec using less than R/2 Hz of bandwidth. Nyquist result tells us that in order to transmit R bits / Sec with no inter symbol interference(ISI), minimum bandwidth required of the transmitted pulse is R/2 Hz. This result implies that duobinary pulses will have ISI. However, this ISI is introduced in a controlled manner so that, it can be subtracted out to recover the original pulse.

Let, the transmitted signal be $x(t) = \Sigma d_k\, q(t- kT)$, $\quad d_k \in \{0,1\}$.

Here , $\{d_k\}$ are the data bits, q(t) is the transmitted pulse and T=(1/R) is the bit period. The pulse q(t) is usually chosen such that there is no ISI at the sampling instances.

$$q(t) = 1 \text{ for } -T/2 < t < T/2;$$
$$= 0 \text{ elsewhere}$$

NRZ is one such scheme and requires a bandwidth of R Hz to transmit R bits/sec.

4.2 Duobinary Encoder :-

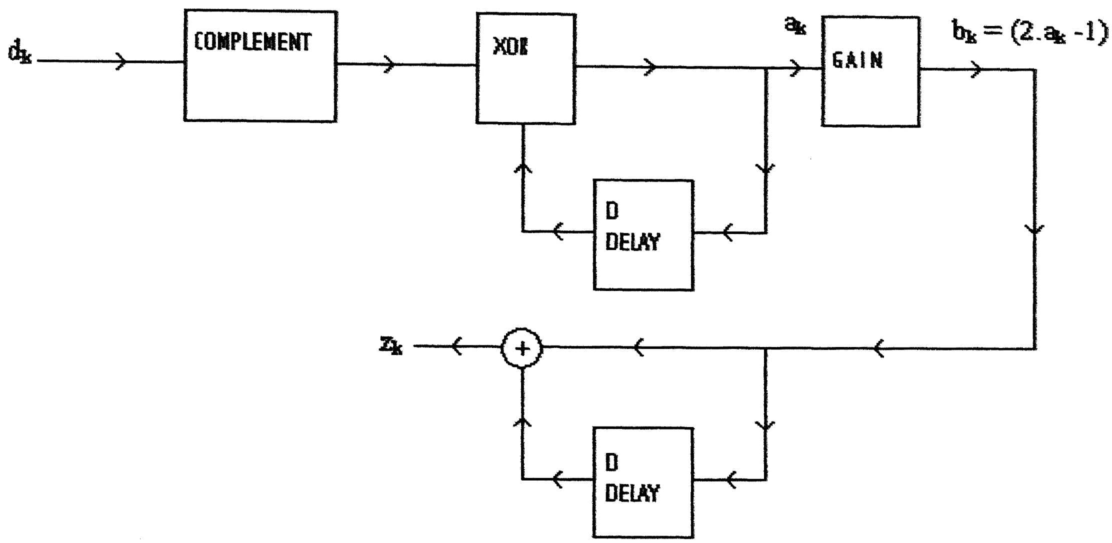

Fig 4.1 Duo binary Encoder

Generation of duobinary modulation from the input bit stream is shown in figure. It has three levels 0 , 1, -1;

T_x	Input Bits (d_k)	0	1	0	1	1	1	0	0	0	0	1	0
	Complement	1	0	1	0	0	0	1	1	1	1	0	1
	Differential Encoder(MSB 0), a_k	1	1	0	0	0	0	1	0	1	0	0	1
	Bit to voltage Mapper (MSB'-1'), b_k	1	1	-1	-1	-1	-1	1	-1	1	-1	-1	1
	Duobinary Encoder (z_k)	0	1	0	-1	-1	-1	0	0	0	0	-1	0
R_x	Receiver Output	0	1	0	1	1	1	0	0	0	0	1	0

Table 4.2 : An example showing transformation of data in a duobinary system

In the chart it is shown how we can generate duo binary signal from the input bit stream. An important property of the three level sequence is that it is a correlated signal and hence all possible sequence can not occur . As an example, 1 followed by -1 ,or (-1)

followed by a # '1' is not possible. A '1' and '(-1)' will always have a 0 in between them. Similarly combinations {1,0,1} and {-1,0,-1} also can not occur.

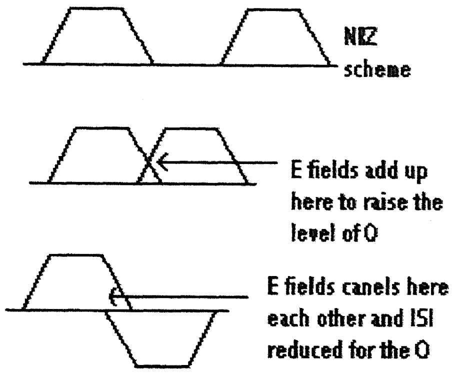

Fig4.3 Effect of dispersion on NRZ duo binary sequences

The figure shows how effect of dispersion can be reduced using duo binary modulation. Without duobinary E field add up to raise the level of zero. But using duobinary modulation as it is having E and –E field, so field cancels here each other and ISI reduced to zero. To modulate the light with the three level duobinary signal, we use Mach-Zehnder modulator biased at it's null point. With a zero input, no light is transmitted but the +1 and -1 inputs are transmitted as +E and –E electric fields. While this is a three level signal in terms of electric field, it is a two level signal in terms of optical power. At the detector two levels will be detected.

CHAPTER 5

Comparative Study of Different Pulse Shapes

5.1 Introduction

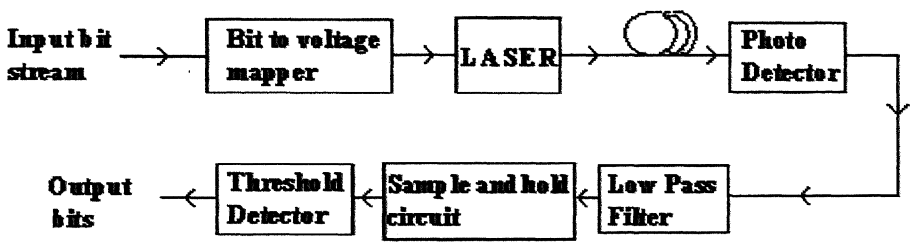

Fig 5.1 Block diagram of an optical communication system

The block diagram shows how bits are transmitted through optical communication system. From the input bits, bit to voltage mapper gives desired pulse shape at the output. While going through optical fiber pulse will get dispersed and, it will suffer inter symbolic interference at the output, which will increase bit error rate.

Being dispersion limited system, we focus on a fiber transmission model which includes first order chromatic dispersion only neglecting all other transmission impairments. Thus, we consider the following transfer function

$H_F(f) = e^{j\,v\,(\pi . f . T)^2}$ where, v = normalize dispersion index ;

If pulse shape is x(t), Furrier Transform X(f) is determined and multiplied with $H_F(f)$ and the impulse response in frequency domain of the filter LPF. After that, using inverse Fourier Transform y(t) is determined. In this way, y(0), y(T), y(2.T) is determined. Here, y(T) and y(2.T) is responsible for ISI. We assume additive Gaussian noise at the detector. So, if power spectral density is known, it is possible to determine the probability of error.

For any five bits there are 32 combinations in case of binary modulation. Considering the ISI effect at the middle bit, probability of error can be determined.

5.2 Different Input Pulses and Their Outputs

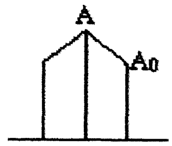

Fig 5.5 . Input pulse shape

We have applied different input pulses with a constant average power 3.73μw. Here, 1 unit of A or, A_0 implies 7.46μw of power level. Six combinations of A and A_0, for constant average power 3.73μw, are applied here. A_0= 0, 0.1, 0.2, 0.3, 0.5 and corresponding A= 1, 0.9, 0.8, 0.7, 0.6, 0.5

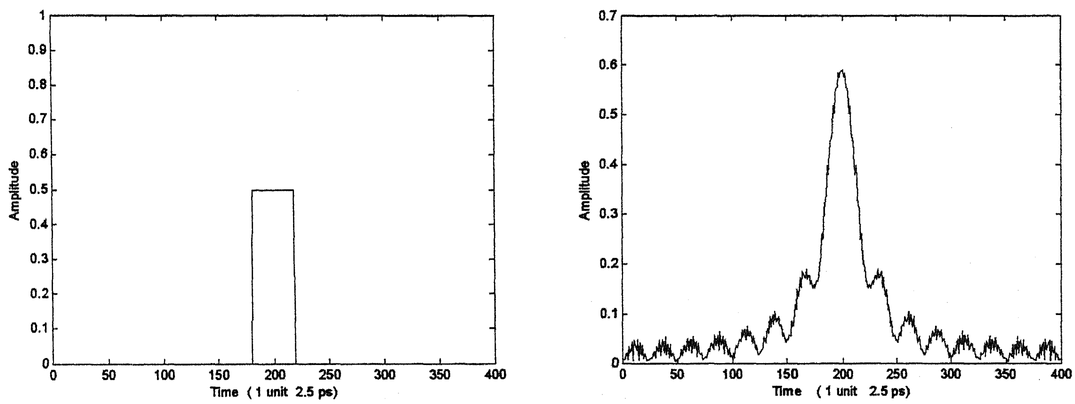

Fig 5.2 Input and output pulse for A=0.5, A0=0.5

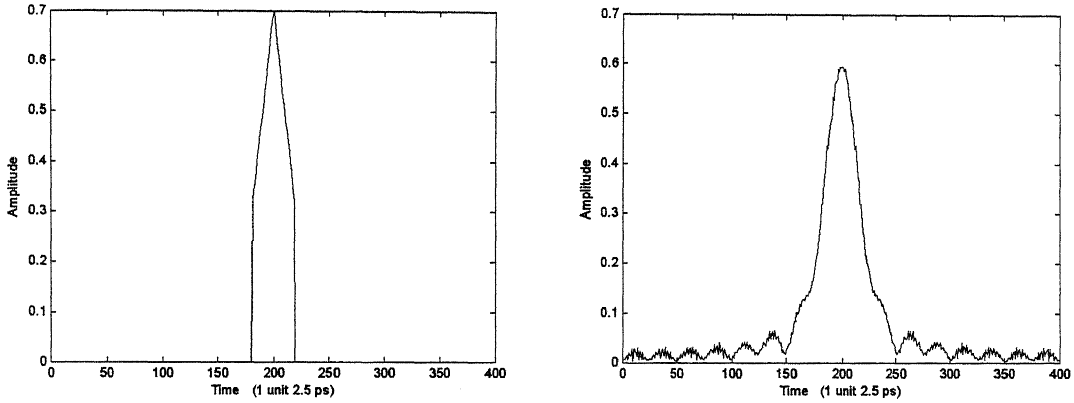

Fig 5.3 Input and output pulse for A=0.7, A0=0.3

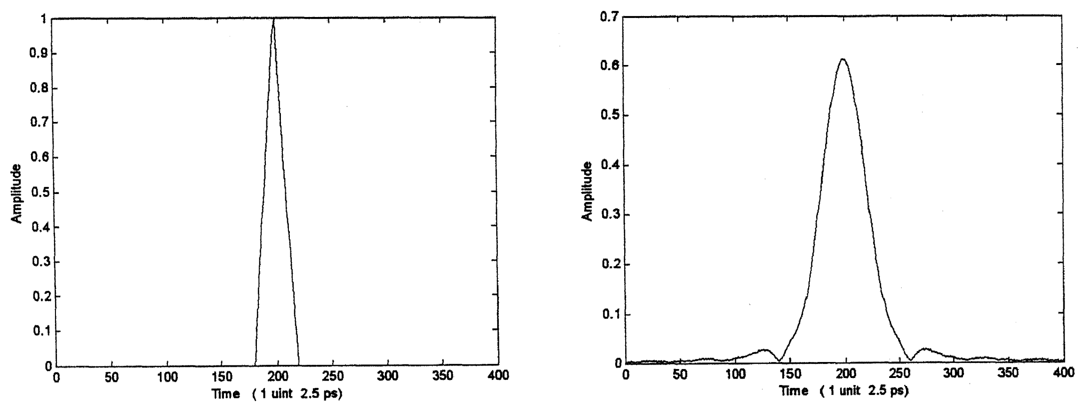

Fig 5.4 Input and output pulse for A=0.5, A0=0.5

So, the input pulses and their corresponding output after dispersion are shown in the figures (fig5.2, fig5.3, fig5.4). Each of the pulses has constant power that is 3.73μw. While these pulses undergoes through dispersive media, spreading takes place. From the figures it is obvious that at y(T) and at y(2.T) signal amplitude is not zero. It will have some positive value due to which ISI takes place. Amplitude at y (0) is also reduced, both of this features increases bit error rate.

5.3 Algorithm

If y(t) is the output pulse after dispersion, Let, y(0)= a, y(T) = b, y(2.T)= c. In the table, each combination of bits and corresponding amplitude level of the middle bit is shown.

Bits	Amplitude	Bits	Amplitude	Bits	Amplitude	Bits	Amplitude
00000	0	01000	b	10000	c	11000	b + c
00001	c	01001	b + c	10001	2.c	11001	b + 2.c
00010	b	01010	2.b	10010	b + c	11010	2.b + c
00011	b + c	01011	2.b+c	10011	b+2.c	11011	2.b + 2.c
00100	a	01100	a + b	10100	a + c	11100	a + b + c
00101	a + c	01101	a + b + c	10101	a + 2.c	11101	a+b+2.c
00110	a + b	01110	a+2.b	10110	a + b + c	11110	a+2.b+c
00111	a + b + c	01111	a+2.b+c	10111	a + b + 2.c	11111	a+2.b+2.c

Table 5.1 Effect of combination of pulses effect on the middle pulse

There can be 32 combinations for 5 bits. It is assumed that after dispersion at 3.T, the amplitude level of the pulse goes to almost zero and can be neglected. So, the middle bit will be distorted by the ISI effect of the adjacent two pulse of each side. For each of

the side, amplitude of the first adjacent at time T and, second adjacent pulse at time 2.T will be added to the amplitude of the middle pulse, which will give rise to increase in bit error rate. So, maximum error will take place for the sequence 11011 where, four adjacent ones will enhance the amplitude level of the zero bit.

From the above table, it is clear that, when 0 is transmitted, there will be probability (1/32) that 0 will be received, probability (1/16) that (a+c) will be received, probability (1/16) that (a+b) will be received, probability (1/8) that (a+b+c) will be received, probability(1/32) that 2.b will be received, probability (1/16) that (2.b+c) will be received, probability (1/32) that 2.c will be received ,probability (1/16) that (b+2.c) will be received and probability (1/32) that (2.b+2.c) will be received.

It is also clear that, when 1 is transmitted, there will be probability (1/32) that a will be received, probability (1/16) that (a+c) will be received, probability (1/16) that (a+b) will be received, probability (1/8) that (a+b+c) will be received, probability (1/32) that (a+2.b) will be received, probability (1/16) that (a+2.b+c) will be received, probability (1/32) that (a+2.c) will be received ,probability (1/16) that (a+b+2.c) will be received and probability (1/32) that (a+2.b+2.c) will be received.

5.4 Power Penalty Plot for Different Conditions:

Different input pulses are applied and output bit error rates are determined. If we put extra energy to a pulse then bit error rate will be improved. For a pulse, if P_0 dB power is required to make BER 10^{-12} when v = 0 and, P_1 dB power is required to make BER 10^{-12} when v = 0.11, then power penalty is (P_1 –P_0)dB. Power penalty is determined for v = 0.11 and v = 0.2 . From the power penalty plot, different pulses are compared.

Band width of the low pass filter is taken as 10 GHz. For,D = 14.9ps/km.nm, L=28.9 km, v = 0.11and, L=52.6 km, v = 0.2 , $N_0 = 82.8\times 10^{-13}$ mv^2 /Hz ;
Power penalty is plotted for bit error rate 10^{-12} in all the cases.

a) Bit Error Rate for Different Types of Filters:

For ideal LPF,

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	3.082×10^{-6}	1.449×10^{-5}	3.224×10^{-4}
A_0=0.1,A=0.9	8.681×10^{-6}	3.133×10^{-5}	4.427×10^{-4}
A_0=0.2,A=0.8	2.326×10^{-5}	6.816×10^{-5}	5.861×10^{-4}
A_0=0.3,A=0.7	5.929×10^{-5}	1.479×10^{-4}	7.374×10^{-4}
A_0=0.4,A=0.6	1.438×10^{-4}	3.172×10^{-4}	9.336×10^{-4}
A_0=0.5,A=0.5	2.213×10^{-4}	5.061×10^{-4}	0.0012

Table 5.2 Bit error rate using ideal LPF at the receiver

For first order LPF,

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	6.905×10^{-5}	5.335×10^{-4}	0.0056
A_0=0.1,A=0.9	2.189×10^{-4}	8.311×10^{-4}	0.0060
A_0=0.2,A=0.8	6.392×10^{-4}	0.0013	0.0069
A_0=0.3,A=0.7	0.0017	0.0019	0.0087
A_0=0.4,A=0.6	0.0043	0.0027	0.0114
A_0=0.5,A=0.5	0.0098	0.0037	0.0154

Table 5.3 Bit error rate using first order LPF at the receiver

For second order LPF,

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	2.395×10^{-6}	3.029×10^{-5}	0.0013
A_0=0.1,A=0.9	1.081×10^{-5}	6.512×10^{-5}	0.0014
A_0=0.2,A=0.8	4.401×10^{-5}	1.362×10^{-4}	0.0017
A_0=0.3,A=0.7	1.612×10^{-4}	2.743×10^{-4}	0.0023
A_0=0.4,A=0.6	5.383×10^{-4}	5.267×10^{-4}	0.0033
A_0=0.5,A=0.5	0.0016	9.59×10^{-4}	0.0050

Table 5.4 Bit error rate using second order LPF at the receiver

As an example, for $A_0 = 0.5$, $A = 0.5$, $v = 0.2$, if 6.497μw excess power is added to the pulse then bit error rate becomes 10^{-12} . Total energy of the pulse becomes 10.23μw. If, we consider 0.2 dB/ Km attenuation in fiber then from computation we can find transmitted power will be 115.3μw, whereas for practically transmit power of laser is 0.4 to 2 mw. Hence, we can neglect the attenuation.

I) Power Penalty Plot for Ideal LPF:

Fig 5.6 shows the power penalty plot for ideal LPF with BER 10^{-12} as pulse shape is modified. From the plot it is clear that as normalized dispersion factor increases dispersion also increases. For, $v = 0.11$ initially the curve decrease and then it increases. At (A-A0) = 0.2, it is minimum and then it increases.

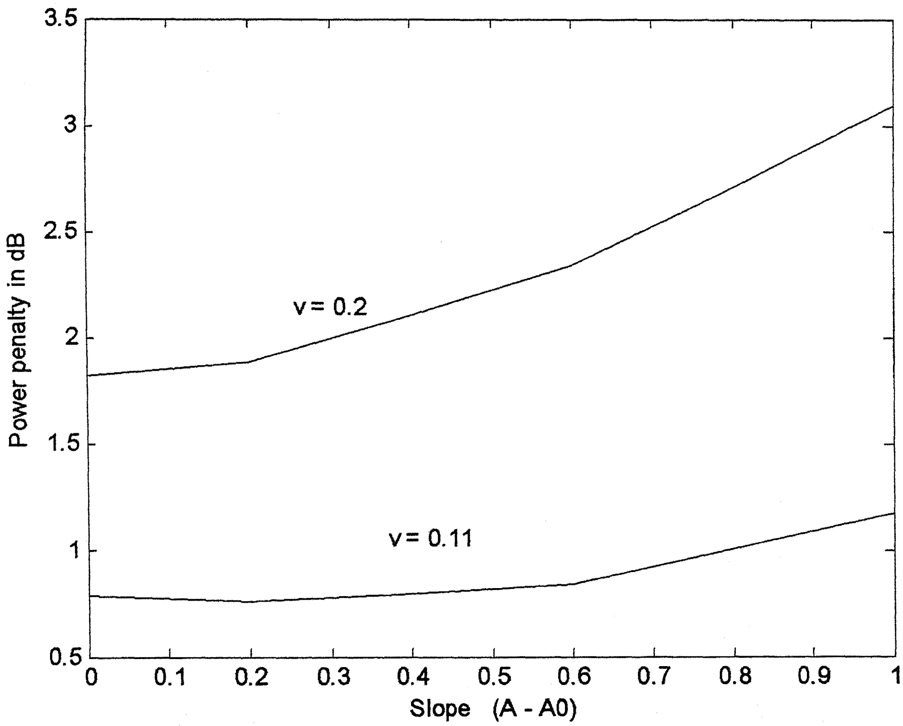

Fig 5.6 Power penalty plot using ideal LPF

II) Power Penalty Plot for First Order LPF :

Fig 5.7 shows the power penalty plot for first order LPF with BER 10^{-12} as a function of pulse shape. From the plot it is clear that as normalized dispersion factor increases, dispersion also increases. For, v = 0.11 initially the curve is below zero level which implies that at this pulse shape when v = 0.11,performance is better than the case when there is no dispersion.

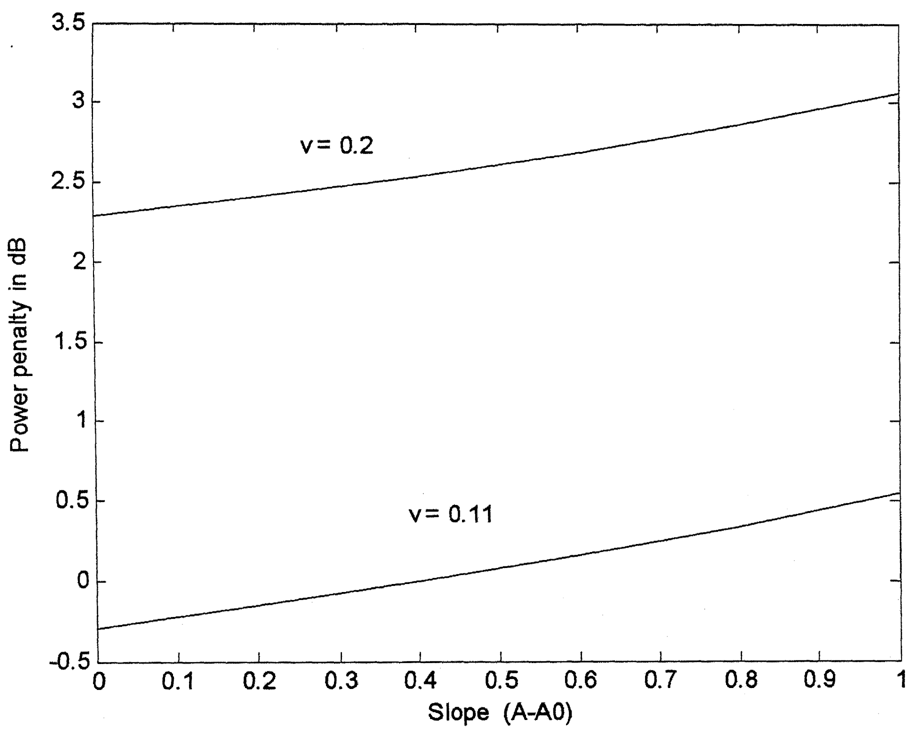

Fig 5.7 Power penalty plot using first order LPF

III) Power penalty plot for second order LPF :

Fig 5.8 shows the power penalty plot for second order LPF with BER 10^{-12} as function of pulse shape. From the plot it is clear that as normalized dispersion factor increases dispersion also increases like previous case. In this case, power penalty plot is increasing continuously for v=0.11 and v=0.2

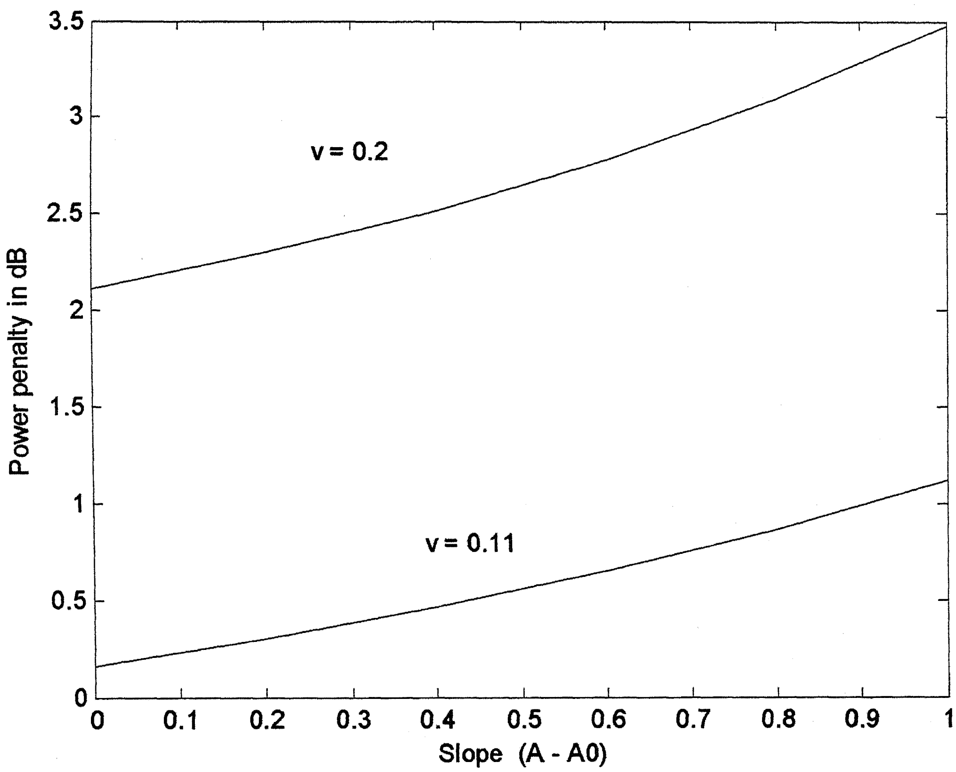

Fig 5.8 Power penalty plot using second order LPF

5.5 Power Penalty for Truncated Gaussian Pulse:

Truncated Gaussian pulse is defined as,

$$x(t) = A.e^{-(t/2.\sigma)^2} - A.e^{-(T/8.\sigma)^2} \quad For\ (-T/2) <= t <= (T/2)$$

$$= 0 \quad Otherwise$$

We have considered five values of sigma , that is σ = 5,6,7,8,9,10 and we have got corresponding amplitude as A= 3.9894,3.3245,2.8496,2.4934,2.2163,1.9947;

V= normalized dispersion factor

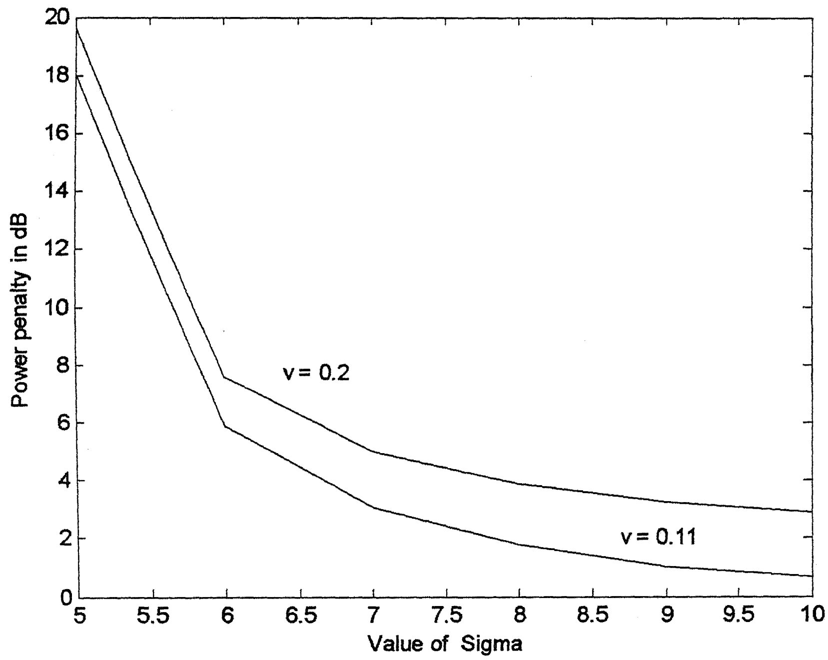

Fig 5.9 Power penalty plot using truncated Gaussian pulse and ideal LPF

From power penalty plot it is clear that for low values of sigma power penalty is very high as sigma increases, power penalty goes down after that, it is tends to become constant.

5.6 Performance Using Duobinary Modulation:

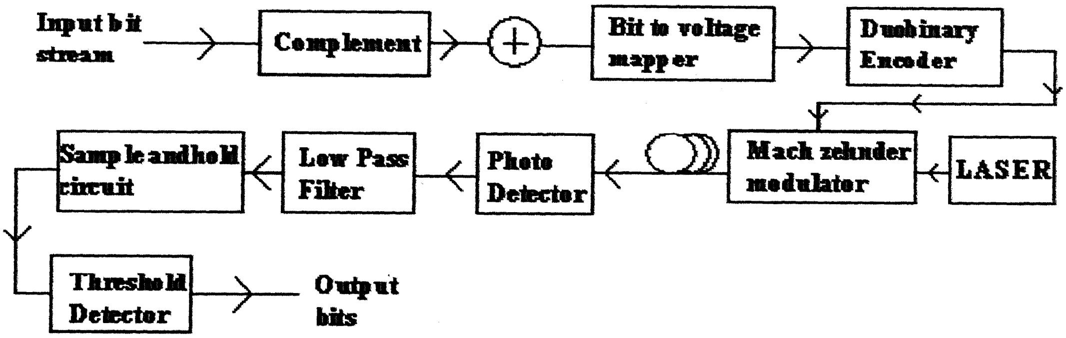

Fig 5.10 Block diagram of duobinary transmission

I) Duobinary modulation is highly efficient in controlling the effect of dispersion. Different pulse shapes as used in chapter 5.2 , are also used here to find out the impact of dispersion. Ideal low pass filter is used as the filter at the receiver.

v= normalized dispersion factor

For ideal LPF,

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	2.864×10^{-6}	1.052×10^{-5}	1.587×10^{-4}
A_0=0.1,A=0.9	8.042×10^{-6}	2.319×10^{-5}	2.261×10^{-4}
A_0=0.2,A=0.8	2.152×10^{-5}	5.803×10^{-5}	3.333×10^{-5}
A_0=0.3,A=0.7	5.485×10^{-5}	1.102×10^{-4}	4.721×10^{-4}
A_0=0.4,A=0.6	1.223×10^{-4}	2.343×10^{-4}	5.910×10^{-4}
A_0=0.5,A=0.5	1.473×10^{-4}	3.136×10^{-4}	7.439×10^{-4}

Table 5.5 Bit error rate using duo binary modulation and ideal LPF

Power penalty plot is shown in the figure 5.11 using duobinary modulation and ideal low pass filter for bit error rate 10^{-12} as function of pulse shape. From the power penalty plot it is clear that with duo binary modulation performance is better. We observe that for v = 0.11 , at (A-A0) = 0.2, power penalty is showing minimum value and also for v = 0.2 , at (A-A0) = 0.2, power penalty is showing minimum value.

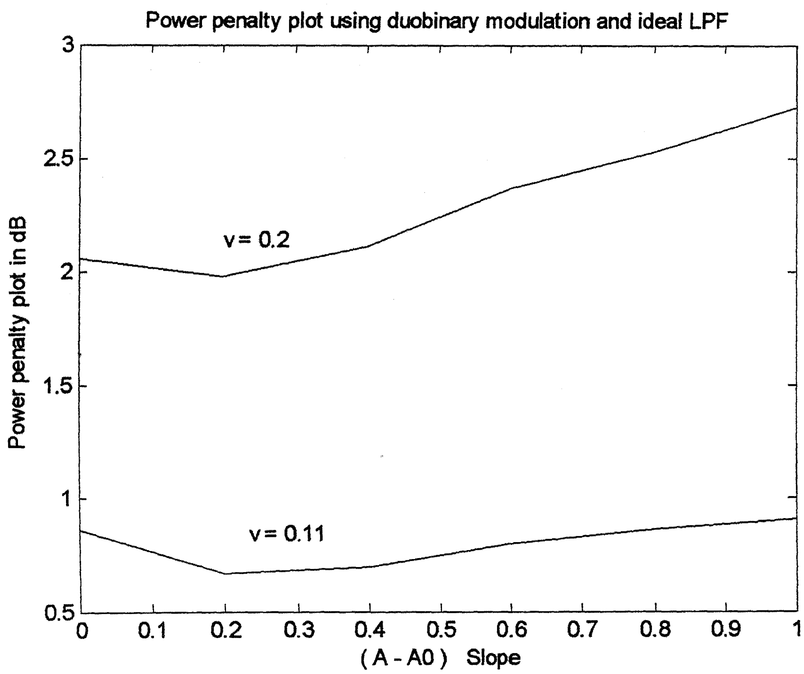

Fig 5.11 Power penalty plot using duo binary modulation and ideal LPF

II) Power penalty plot for first order LPF at the receiver using duobinary modulation is shown in fig 5.12. For, v = 0.11 initially the plot is negative which means pulse shows better performance in v = 0.11 than v = 0; It is also showing better performance than the ideal low pass filter.

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	5.073×10^{-6}	2.87×10^{-5}	2.05×10^{-4}
A_0=0.1,A=0.9	1.61×10^{-5}	4.544×10^{-5}	2.926×10^{-4}
A_0=0.2,A=0.8	4.738×10^{-5}	7.097×10^{-5}	4.167×10^{-5}
A_0=0.3,A=0.7	1.327×10^{-5}	1.093×10^{-4}	6.086×10^{-4}
A_0=0.4,A=0.6	3.454×10^{-4}	1.649×10^{-4}	9.114×10^{-4}
A_0=0.5,A=0.5	8.427×10^{-4}	2.413×10^{-4}	0.0014

Table 5.6 Bit error rate using duobinary modulation and first order LPF

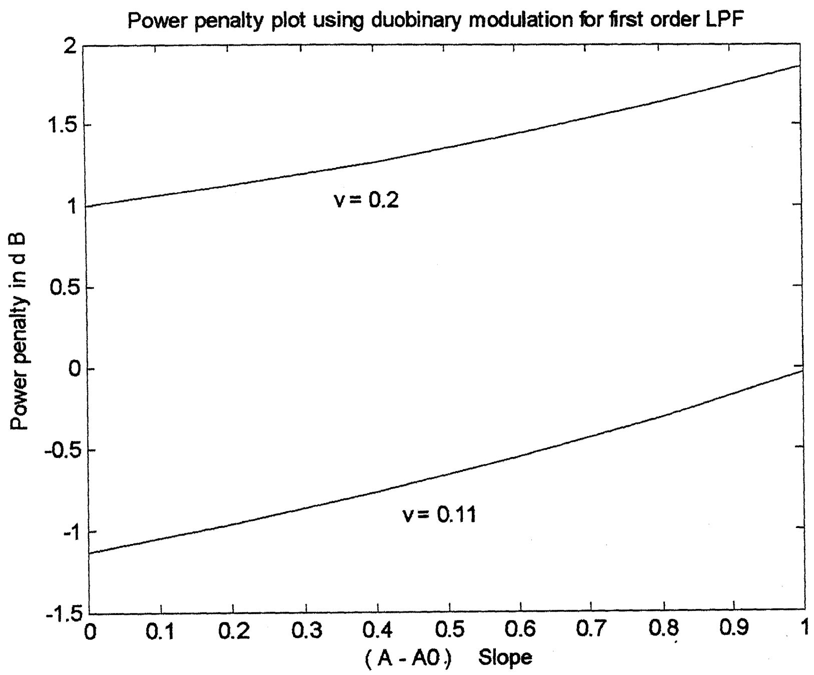

Fig 5.12 Power penalty plot using duobinary modulation and first order LPF

III) Power penalty plot for second order LPF at the receiver using duobinary modulation is shown in fig 5.13. Here, we find that power penalty is increases continuously as slope increases.

Different Values of A and A0, (Average power 3.73μw)	Different normalized dispersion index v		
	v=0	v=0.11	v=0.2
A_0= 0,A=1	6.397×10^{-7}	3.696×10^{-6}	3.827×10^{-5}
A_0=0.1,A=0.9	2.0553×10^{-6}	7.0726×10^{-6}	5.555×10^{-5}
A_0=0.2,A=0.8	6.265×10^{-6}	1.288×10^{-5}	8.2326×10^{-5}
A_0=0.3,A=0.7	1.564×10^{-5}	2.299×10^{-5}	1.2373×10^{-4}
A_0=0.4,A=0.6	3.773×10^{-5}	4.017×10^{-3}	1.8731×10^{-4}
A_0=0.5,A=0.5	8.772×10^{-5}	6.865×10^{-5}	2.839×10^{-4}

Table 5.7 Bit error rate using duobinary modulation and second order LPF

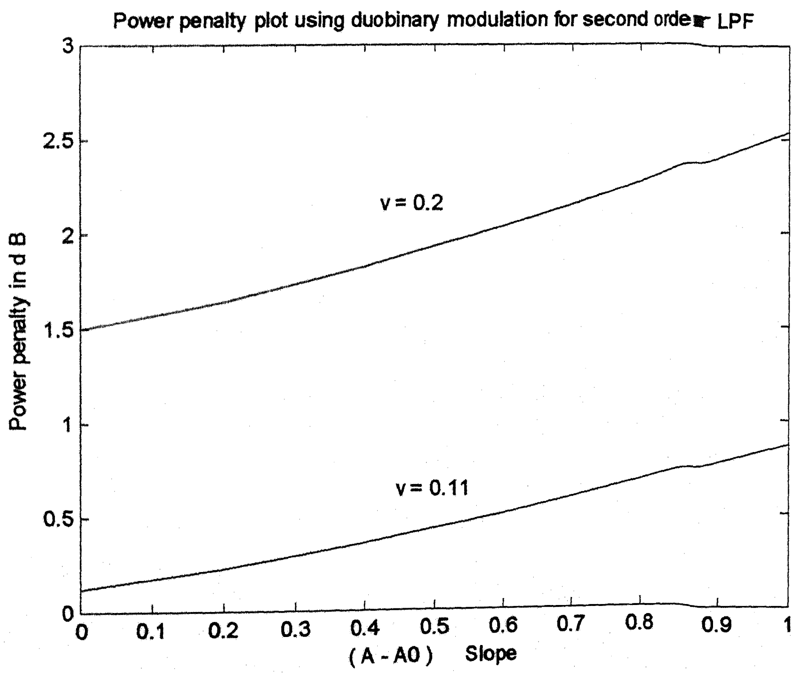

Fig 5.13 Power penalty plot using duobinary modulation and second order LPF

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 CONCLUSIONS

In this thesis , the effect of dispersion on different pulse shapes in an optical fiber link are studied. It is found that as normalized dispersion index increases, the power penalty (i.e., the amount of extra power needed to maintain same BER over the case of no dispersion) also increases. This is observed with all type i.e. ideal LPF, first order LPF, second order LPF at receiver.

- For a truncated Gaussian pulse, the power penalty is high for low values of pulse width and as pulse width increases, it's performance is close to that of a rectangular pulse.
- Also, it is found that power penalty is negative for some pulse shapes, when first order LPF is used at receiving end. This indicates a better performance of dispersive channel as compared to nondispersive case.

Further, the effect of dispersion on pulse shapes in a duobinary modulated optical channel is studied. As expected, the performance is better than optical channel with NRZ modulator.

To summarize, a duobinary modulated optical channel gives overall best performance when a second order LPF is used.

6.2 SUGGESTIONS FOR FUTURE WORK

- This scheme can be incorporated in presence of modulation like WDM, OFDM.
- We have considered low attenuation. If there is considerable amount of attenuation we have to use optical amplifiers. This study can be extended in presence of optical amplifiers.
- This work has to be extended to find a generalized pulse shape which will minimize the effect of dispersion.

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